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Crosslinked polyethylene as an insulation for high voltage underground cable.

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CROSSLINKED POLYETHYLENE AS AN INSULATION FOR HIGH VOLTAGE UNDERGROUND CABLE

BY

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ABSTRACT

There is an ever increasing demand for the electric utilities to install their high voltage transmission lines underground due to the environmental impact of overhead lines. Traditionally, these underground lines have been either pipe-type or self-contained oil filled, paper insulated cables. Recently solid dielectric cable, utilizing crosslinked polyethylene as the insulation, has appeared on the market for transmission cables up to the voltage level of 138kV.

This new product brought with it the advantages of reduced charging currents, lower installation and maintenance costs, lower insulation cost, and ease of installation, splicing and terminating. The disadvantages are those common to new products -- unknown reliability, unknown durability -- plus a potentially serious phenomenon called electrochemical treeing. This is the electrochemical breakdown of the insulation that develops slowly in wet environments, proceeds over long periods of time and is believed to be caused by minute voids and contaminants within the insulation. This breakdown of the insulation between the high voltage conductor and the grounded concentric shielding could eventually result in the cable failure.

In this paper, the characteristics of crosslinked polyethylene are reviewed, the advantages and disadvantages of solid dielectric high voltage cable are investigated, and several actual installations are discussed. The conclusions that emerge show that crosslinked polyethylene is an excellent insulation for high voltage cables. Treeing can be controlled if the manufacturers maintain a low contamination level and assemble the cable using a triple extrusion method. Increased use of crosslinked polyethylene insulated cables up to the voltage level of 138kV is a certainty. Furthermore, it is expected that solid dielectric extra high voltage cable up to the voltage level of 230kV will appear on the market within the next decade.

CHAPTER 1

INTRODUCTION

Increased pressure for electric utilities to install their high voltage transmission lines underground has come from environmental groups, political and civic leaders and right-of-way restrictions. The increased transmission voltage and the development of new insulating materials have required the utility engineers to make constant re-evaluations of their underground systems. Traditionally, underground lines have been either pipe-type or self-contained oil filled, paper insulated cables.* An increasing number of electric utilities are using crosslinked polyethylene as a cable insulation. Recently solid dielectric crosslinked polyethylene cable has appeared on the market for transmission lines up to the voltage level of 138kV.

*The oldest reported underground transmission installation in the USA is a 138kV, low pressure oil filled cable installed by the Consolidated Edison Company in 1926.

Although solid dielectric and crosslinked polyethylene in particular, have been a success in the field of underground power cable insulation, it is evident from Tables 1 and 2 that they have not acquired industry wide acceptance. It will take many years of reliable service to achieve this goal.

Table 1

Results of Round Table Questionnaire

Companies that have solid dielectric power cables installed which are operating at their rated voltage:

Rated Voltage	Number of Companies
69kV	20
115kV	2
138kV	6

Companies that use solid dielectric power cables with a higher voltage rating than their operating voltage:

Percent Rated Voltage	Number of Companies
105-110% of Operating Voltage	2
111-125% of Operating Voltage	4
126-150% of Operating Voltage	1

Round table questionnaire submitted by the Electrical System and Equipment Committee of EEI during the October 1974 meeting in Toledo, Ohio. Sixty-eight companies responded to the questionnaire.

Table 2

Results of General Cable Corporation Questionnaire

Companies that have strong preference relative to type of cable for underground transmission in use at the present time:

Companies	Percent of Installed Cable That is Preferred Type	Preferred Type of Cable
23	80% or more	Low pressure oil filled
2	70% or more	High pressure oil filled
2	100%	Crosslinked Polyethylene
1	100%	Medium pressure oil filled

Companies reporting installation of crosslinked polyethylene insulated cables:

Number of Companies	Cable Rating
7	138kV
3	115kV

Results of questionnaire entitled "Underground Transmission Design, Development, Installation and Use at 115kV and Above". The questionnaire was prepared and circulated by Dr. George Eager of General Cable Corporation in April 1973. Thirty-seven companies responded to questionnaire.

CHAPTER 2

DESCRIPTION OF CROSSLINKED POLYETHYLENE

As long ago as 1888, power cables insulated by vulcanized rubber were employed by the New York Subway Commission.[1] Rubber insulated cables are still in great demand, with synthetics being preferred over natural rubber. Not until the discovery that ethylene could be copolymerized into an ordered structure did it seem feasible to improve the electrical breakdown strength of synthetic rubbers to the point where they would become useful for high voltage cables.

Thermoplastic polyethylene has been used for over 25 years in the power cable industry. It became evident that certain molecular configurations gave superior high voltage cable performance. Among the more important molecular characteristics are the crystallinity, the molecular weight, and the molecular weight distribution.[2] Also the use of basic ingredients other than ethylene has led to a family of "copolymers which are still true polyethylenes - i.e., chains of CH_2 groups.

Density varies directly with crystallinity of a resin and this in turn is an inverse function of the number of short chain branches of the polyethylene molecule. The polyethylene molecule consists of CH_2 groups strung together in a long chain, with occasional branches. The fewer these branches are, the more possible it is to align adjacent molecules to form crystalline regions. The more aligned the molecules are, the more closely packed they become, and the denser the material will be.

The ultimate in density one could reach is to have almost no branches, or the so-called linear resin. Since the linear molecules -- that is, those without side chains -- are readily aligned, the crystallinity and density of the resultant resin are high. This is why "linear" polyethylenes are inherently "high density" resins. For convenience, densities in the range well below 0.92 are often spoken of as "low"; approximately 0.92 to 0.94, as "medium"; and above 0.94, as "high".

The properties that are density or crystallinity dependent are stiffness, tensile strength, abrasion resistance, softening and melt points. Elongation drops off with density increase.

While the properties of a high density or linear resin would be desirable from the mechanical viewpoint of cutthrough and high temperature service, it is not clear how to lick the problem of shrinkage in heavy sections leading to voids; this is one reason the linear resin is not used for high voltage underground cables. The greater stiffness of the linear or high density resins, while carrying with it the advantage of abrasion resistance, also may lead to some problems in processing, handling, stripping, thermal crack resistance, and electrical performance. For these reasons, and because many of the advantages of high density resins can be achieved -- without the disadvantages -- by other changes in the molecule, medium density polymers (0.92 - 0.93) are used in high voltage cables.

Molecular weight varies directly with the length of a chain of ethylene molecules which have been strung together or polymerized into a long polyethylene molecule. In any given sample of polyethylene there will be many different chain lengths present, from quite short to very long. The average chain length determines the average molecular weight. As molecular weight is increased, tensile strength and elongation (i.e. "toughness") are increased, as well as resistance to stress cracking in the presence of detergents; and the resistance to cracking at extremely low temperatures is further improved. The disadvantage to high molecular weight material is slightly higher cost. Two different polyethylenes can have the same average molecular weight, but differ markedly in molecular weight distribution -- i.e., in the mixture of long and short molecules. This molecular weight distribution is the third important factor in selecting a polyethylene for high voltage cables. It has been found that in the medium density resins giving the best combinations of properties for high voltage cables, to combine a high molecular weight -- that is, a long average chain length -- and a relatively narrow molecular weight distribution (that is, most of the chain lengths nearly the same size) gives the best physical properties, particularly crack resistance, both to chemical environments and for low temperature applications.

The major expansion in the use of solid dielectric power cables occurred during the last 15 years, concurrent with the introduction of crosslinked polyethylene insulation. The mechanical and electrical properties of crosslinked polyethylene closely resemble those of very high molecular weight polyethylene before vulcanization. The merits of crosslinking of the polymer molecules were established with the help of electron-irradiated samples, but the economical production of crosslinked polyethylene insulation had to wait for the evolution of peroxide compounds that could be chemically crosslinked in a steam tube. One such compound is dicumyl peroxide.[4] The dicumyl peroxide functions as the vulcanizing agent. When heated, this material forms free radicals that cause the thermoplastic polyethylene to crosslink, changing it to a thermoset, a material which has an extremely high melting temperature.

Modern crosslinked polyethylenes offer excellent high temperature stability and good stability in the presence of oxygen and ozone. This inherent stability is the result of the low amount of branching and lack of unsaturation in the polyethylene molecule (see figure 1 on page 12).

The crystalline nature of polyethylene leads to excellent chemical and solvent resistance. Crosslinking of polyethylene further improves this characteristic by rendering it unsoluble even in solvents normally used for high molecular weight polyethylene.

Minimum (physical) requirements for crosslinked thermosetting polyethylene insulation used for underground cable have been established by IPCEA (Insulated

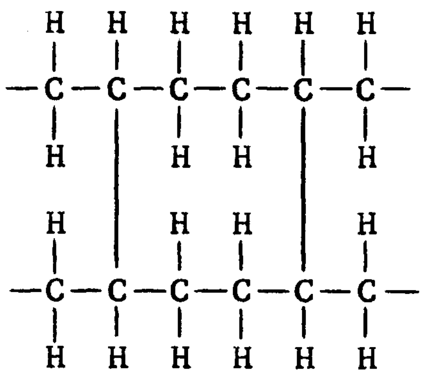


Figure 1

Molecular Structure of Crosslinked Polyethylene

Crosslinked polyethylene has connecting bonds that distinguish it from plain C-H chains.
Source: Reference 3.

Power Cable Engineers Association) and NEMA (National Electrical Manufacturers Association) and have been accepted by the cable and utility industries. These values are listed in Table 3 on page 14. Although the measured physical properties of crosslinked polyethylene will vary with compound and manufacturer, the values listed as "measured" in Table 3 are representative of those cables presently produced for high voltage underground transmission. The electrical requirements for crosslinked polyethylene insulation have also been established and accepted. The following tests must be made by the cable manufacturer on all cables produced.[5] A test sample shall be taken from the insulated conductor prior to the application of any covering. The capacitance and power factor shall be measured on suitable 60-hertz equipment after the sample has been immersed in water at room temperature for at least 14 days. The measurements shall be made at the rated voltage to ground of the cable under test.

The dielectric constant, also termed specific inductive capacitance (SIC), is the ratio of the capacitance with an intervening dielectric material as compared to the capacitance with vacuum as the intervening dielectric material.[6] The dielectric constant of the in-

Table 3

Physical Properties of Crosslinked Polyethylene Cable Insulation

	Physical Requirement of Insulation per IPCEA - NEMA Standards[5]	Average Measured Values*
Original Tensile Strength, psi	>1800	2600
Elongation at rupture, %	> 250	535
After air oven test at $121^{\circ} \pm 1^{\circ}C.$ for 7 days		
Tensile strength, % of original	>75	95
Elongation at rupture, % of original	>75	95
Heat Distortion, $121^{\circ}C. \pm 1^{\circ}C.$ % of original value	<15	5
Density, g/cc	----	.915
Stress, psi at 100% strain	----	50
Modulus of Rigidity, psi	----	16,500

*Values obtained from 1) Interim Product Sheet Alathon® PE-6117-3, 2) Polycure® 522 Data Sheet and 3) Polycure® 63-521 Data Sheet, Alathon is a registered trademark of the Du Pont Co. and Polycure is a registered trademark of the Cooke Color and Chemical Co.

sulation shall be calculated as follows:

$$\text{Dielectric Constant} = 13600\ C \log_{10} \frac{D}{d}$$

where:

C = Measured capacitance in microfarads of the 10 foot section
D = Diameter over the insulation in mils
d = Diameter under the insulation in mils

The maximum permissible dielectric constant is 3.5 while the average calculated value for the crosslinked polyethylene used in high voltage cable is 2.28.

The power factor of a dielectric is the ratio of power dissipated to the product of applied voltage and resultant current when tested under a sinusoidal voltage.[6] Vectorally the voltage will lag the current by an angle θ. The cosine of θ is the power factor and is often expressed as a per cent value. The maximum permissible power factor for crosslinked polyethylene is 2.0%. The average measured value for Polycure® 522 and Polycure® 63-521 crosslinked polyethylene is 0.06%.

An insulation resistance test must also be performed on all cable produced. This test is taken on the completed cable. Each reel of cable shall have an insulation resistance in megohms per 1000 feet at a temperature of 15.6° C. (60° F.) of not less than the value of R calculated as follows:

$$R = K \log_{10} \frac{D}{d}$$

where:

R = Insulation resistance in megohms per 1000 feet
K = 20,000 (resistance constant for crosslinked polyethylene)
D = Diameter over the insulation in mils
d = Diameter under the insulation in mils

The dielectric breakdown strength is the 60-hertz voltage at which a disruptive discharge occurs through or over the surface of the insulation.[6] The voltage is applied in a specified manner, which is basically a quick-rise voltage technique. The breakdown voltage is generally expressed in volts per mil. This is obtained by taking the value of the breakdown voltage and dividing it by the sample thickness, in mils, at the point of breakdown. The average dielectric breakdown strength of the crosslinked polyethylene used in high voltage cable is 1100 volts per mil.

CHAPTER 3

GENERAL REQUIREMENTS FOR HIGH VOLTAGE UNDERGROUND CABLES

The typical construction of an extruded, crosslinked polyethylene insulated power transmission cable is illustrated in Figure 2. It contains a stranded copper or aluminum conductor which is covered by an extruded layer of semiconducting (carbon-black filled) polyethylene. This semiconducting layer, called the conductor shield, presents a smooth conductor surface to the insulation and excludes air, which would produce internal corona, from the interface. Often a semiconducting nylon tape is included, as part of the conductor shield, and is inserted between the conductor and the semiconducting polyethylene. This tape prevents the strands from unraveling during the extrusion process.

The insulation is extruded directly over the conductor shield. Another semiconducting polyethylene layer, the insulation shield is extruded over the insulation. As with the conductor shield, its function is to prevent gas discharges on the insulation surface.

Technological advances in the cable manufacturing industry have resulted in the development of a vertical-

Figure 2

Typical Construction of an Extruded Crosslinked Polyethylene Insulated Power Transmission Cable tandem-extrusion process for applying the conductor shield, the primary insulation and the insulation shield. This operation has several technical advantages including complete cleanliness through the interfaces and elimination of the hazards of moisture and mechanical damage between operations. Another new factor has been the development of a semiconducting crosslinked copolymer for the extruded shields. This practical development is now commercially available and provides an integral shield, affording a bond between the shields and insulation which is essential in ideal shielding. The conductor shield is applied and the primary insulation superimposed immediately in a tandem extruder operation. These two materials are formed into an integral unit of crosslinked plastic during the subsequent continuous vulcanizing process. The extruded insulation shield is applied as a separate operation and is processed to remain unbounded to the insulation, although very tightly in contact. This triple-extrusion process produces very good corona performance while maintaining the advantages of outer shield separability for splice or termination preparation in the field.

A metallic layer on top of the insulation shield carries the longitudinal charging current. If the semi-conducting layer had to sustain this current, it would overheat and burn. The metallic layer consists of helically wound copper tapes plus bare copper wire inserted longitudinally the entire length of the cable.

The metallic layer is protected against corrosion by a layer of mylar or cotton tape plus a layer of polyethylene or polyvinylchloride.

The simplified construction of the crosslinked polyethylene insulated cable, compared with oil and paper insulated systems, has been its major attraction. It is a dry cable and requires no gaseous or liquid impregnants nor a pipe for containing the impregnant pressure.

Where underground cable is installed as part of a transmission system, great care must be taken so that the cable is not a capacity limitation for the system. In other words, the size, construction and installation of the cable must be such that the cable rating will at least match the ampacity rating of the rest of the system.

Although the actual load carrying capacity of any component depends on the design and construction of the component, maximum operating temperatures have been developed and agreed upon. The maximum conductor temperature at which the crosslinked polyethylene should operate satisfactorily in wet or dry locations are shown below.[7]

Normal Operation	Emergency Operation	Short Circuit Operation
90° C. (194° F.)	130° C. (266° F.)	250° C. (482° F.)

The heading "Normal Operation" pertains to operating load cycles typical of electric light and power systems. The temperatures under the heading "Emergency Operation" are applicable for an average, over several years, of one period of not more than 72 hours per year for cables rated 69kV (and above),and for a total of not more than three periods in any twelve consecutive months. The maximum conductor temperature is defined to be the actual hottest portion of the circuit at any time.

These temperatures roughly correspond to maximum allowable conductor temperatures for overhead transmission lines - especially those with Aluminum Conductor Steel Reinforced (ACSR) conductor. For example, the overhead line ratings used by a utility power pool until 1974* for ACSR conductor is based on the following

* In 1974, the power pool revised its line rating philosophy. As a result, they no longer differentiate maximum conductor temperatures for normal and emergency operation.

maximum conductor temperatures:

Conductor	Max. Temp. Normal Operation	Max. Temp. Emergency Operation
ACSR	100° C. (212° F.)	125° C. (257° F.)

These temperature limitations are the basis for the conductor capacity limitations. When designing a transmission system, especially a network arrangement, it may be necessary to match the underground cable capacity with that of the overhead lines. Conversely, if a radial system is being developed this may not be necessary. For example, suppose a 138kV overhead line is designed to distribute power from a source. A typical conductor used would be 556.5 kcmil ACSR which has a summer, normal operation, thermal rating of 670 amps.[8] This line could feed various substations with the final line section being an underground feed to an urban downtown substation. The underground line section would be designed with sufficient capacity to match the future load of the substation. This would be substantially lower than 670 amps at 138kV.

CHAPTER 4

THE ADVANTAGES OF CROSSLINKED POLYETHYLENE OVER OTHER SOLID DIELECTRICS FOR POWER CABLE INSULATION

When comparing the electrical properties of various insulations, the dielectric constant is of the utmost importance. The dielectric constant has a strong influence on the line charging current and the insulation loss factor. As defined on page 15, the dielectric constant and the cable capacitance are directly proportional for a given cable construction. The potential difference between the conductor and the grounded metallic shield causes the cable to be charged in the same manner as the plates of a capacitor are charged when there is a potential difference between them. An alternating voltage impressed on a conductor causes the charge on the conductor at any point to increase and decrease with the increase and decrease of the instantaneous value of the voltage between the conductor and ground. The flow of charge is a current, and the current caused by the alternate charging and discharging due to the alternating voltage is called the charging current of the line.[9] It affects the voltage drop along the line as well as the efficiency and power factor of the line and the stability of the system of which the line is a part.

Thus, the term charging current is applied to the current associated with the capacitance of the line and can be calculated:

$$I_{chg} = j\omega CV = j2\pi fCV$$

or

$$I_{chg} = \frac{2\pi fV}{1000} \times \frac{0.00736\ K}{\log_{10}\ D/d}$$

where:

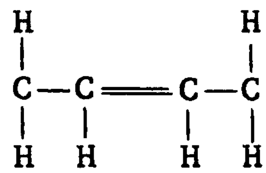
- K = dielectric constant of the insulation
- I_{chg} = charging current in amperes
- V = Circuit voltage to ground in kilovolts
- f = frequency in hertz
- D = diameter over the insulation
- d = diameter under the insulation

The loss factor is simply defined as the product of the dielectric constant and the power factor of the insulation. The loss factor is expressed as a per cent value.

As was previously mentioned, solid dielectric material has been used for power cable insulation for a good many years. Some of the most commonly used solid dielectrics are natural rubber, butyl rubber, styrene butadiene rubber, ethylene propylene rubber, polypropylene, high-molecular-weight polyethylene and, of course, crosslinked polyethylene. Theoretically, any one of these materials could be used for high voltage cable insulation. The inherent characteristics of the materials make some more desirable than others. These characteristics will be investigated and compared in the following discussions.

Crosslinked polyethylene is tougher and stronger than rubber. It also has a better low temperature performance and crush, cut-through, impact and abrasion resistance than rubber. Compared to rubber, crosslinked polyethylene has a higher dielectric strength, lower loss factor and better insulation resistance. It also has a lower cost than rubber.

The synthetic rubbers, such as butyl rubber and styrene butadiene rubber are inherently less stable than crosslinked polyethylene. This is because these synthetic rubbers contain "unsaturation" (double bonds) which makes them highly susceptible to oxygen and ozone attack. Recall Figure 1 (page 12) and see Figure 3 (page 26). For example, crosslinked polyethylene contains less than 1% unsaturation versus 1 to 3% for butyl rubber; and up to 50% for styrene butadiene rubber, natural rubber and polychloroprene.



<u>Figure 3</u>

Double Bonds Which Effect Stability

Unsaturation (double bonds) between C's make styrene butadiene rubber and butyl rubber less stable for insulation. Source: Reference 3.

As can be seen in Table 4, crosslinked polyethylene exhibits superior electrical properties to butyl rubber.

Table 4

Electrical Properties of Crosslinked Polyethylene as Compared to Those of Butyl Rubber.

	Crosslinked Polyethylene	Butyl Rubber
Dielectric Constant (60 Hertz)	2.28	3.5 - 3.9
Power Factor (60 Hertz)	0.06%	0.7 - 1.5%
Loss Factor (60 Hertz)	0.14%	2.45-5.85%
Dielectric Breakdown Strength (volts per mil)	1100	900 - 1200

Ethylene propylene rubber and polypropylene contain more side chain branching in their molecular structure than crosslinked polyethylene, and are inherently less stable. The difference in stability is due to the tertiary hydrogen atoms opposite each of these branches, which are the oxidatively vulnerable sites. Ethylene propylene rubber and polypropylene contain about 13 and 25 times, respectively, more tertiary hydrocarbons than crosslinked polyethylene. Recall Figure 1 (page 12) and see Figure 4. Accordingly, these materials have poorer stability at high temperatures.

Tertiary or Active Hydrogen

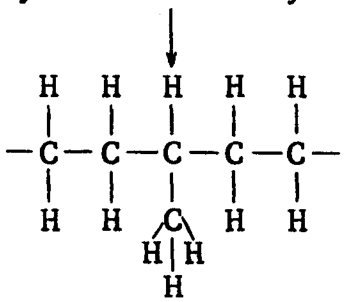


Figure 4

Side Branches Which Effects Stability

The side branches with the hydrogen atoms that are inherent with ethylene propylene rubber and polypropylene produce poor stability at high temperatures.
Source: Reference 3.

Crosslinked polyethylene also exhibits superior electrical and thermal properties to those of ethylene propylene rubber, as can be seen from Table 5. This is partially due to the fact that ethylene propylene rubber is a clay-filled dielectric. The addition of such fillers as clay, carbon black or talc, raises some of the physical and mechanical properties of rubber dielectrics, but always at some sacrifice in electrical properties.

Table 5

Electrical and Thermal Properties of Crosslinked Polyethylene as Compared to Those of Ethylene Propylene Rubber.

	Crosslinked Polyethylene	Ethylene Propylene Rubber
Dielectric Constant (60 Hertz)	2.28	3.3
Power Factor (60 Hertz)	0.06%	0.68%
Loss Factor (60 Hertz)	0.14%	2.25%
Thermal Resistivity (ohms)	350	610

High-molecular-weight polyethylene exhibits identical electrical properties as crosslinked polyethylene. In practice, both materials are used as solid dielectric cable insulation for high voltage underground lines. The most significant difference between the characteristics of the two dielectrics is that crosslinked polyethylene has a much higher allowable operating temperature (see Table 6).

Table 6

Electrical and Thermal Properties of Crosslinked Polyethylene as Compared to Those of High-Molecular-Weight Polyethylene.

	Crosslinked Polyethylene	High-Molecular-Weight Polyethylene
Dielectric Constant (60 Hertz)	2.28	2.28
Power Factor (60 Hertz)	0.06%	0.06%
Loss Factor (60 Hertz)	0.14%	0.14%
Thermal Resistivity (ohms)	350	350
Normal Operating Temp.	90° C.	80° C.
Softening Temp.	135° C.	90° C.

Crosslinking also helps eliminate any tendency of the insulation to crack due to environmental and thermal stresses and makes the polyethylene more flexible and solvent resistant. As far as economic considerations are concerned, the continuous vulcanizing process required for crosslinked polyethylene adds significantly to the manufacturing cost. The actual cost of the insulating material is not a very significant factor.

The comparison between high molecular-weight polyethylene and crosslinked polyethylene boils down to a tradeoff of higher manufacturing cost for vulcanizing against a smaller conductor made possible by the higher insulation softening temperature. At the present economy, the smaller conductor and crosslinked polyethylene produces a net saving.

CHAPTER 5

THE ADVANTAGES OF CROSSLINKED POLYETHYLENE OVER OIL AND PAPER DIELECTRIC FOR POWER CABLE INSULATION

Presently oil and paper is the most commonly used dielectric for high voltage power cables. Of these, the low or medium pressure, self contained cables are most popular.

These single conductor cables are mostly direct buried (installed directly in trenches) and the impregnating oil is pressurized via an open, oil filled duct in the center of the conductor. The insulation is enclosed in a lead or aluminum sheath. The sheath provides mechanical and environmental protection for the cable. This is protected by a polyethylene or polyvinylchloride corrosion protective covering. The oil pressure is maintained by use of a pumping plant, pre-pressurized reservoirs or gravity feed reservoirs. Alarms are generally used to give indication of abnormal temperature conditions.

High pressure, oil filled, pipe type cables predominate in the United States in the extra high voltage range. In this system, the paper insulated conductors are enclosed in a welded steel pipe protected by a high grade corrosion protective covering. The pipe is usually provided with cathodic protection. Pressure is maintained by use of a pumping plant which can be located at any convenient location on the route. Frequently, these cable systems are installed in pairs, the two pipes placed approximately one foot apart to provide increased reliability through redundancy, and economy through sharing of a single trench. However, since the ampacity of the cables is usually limited by the temperature that the paper insulation will tolerate or by the temperature of the surrounding soil, locating two circuits close to one another reduces the maximum ampacity. This effect can be partially offset by pumping the pressurized oil down one pipe, back through the other, and then through a heat exchanger. Alarms are required for the pressurization system to give indications of abnormal conditions and to prevent damage to the cable due to ionization.

Both of the above mentioned systems require a rigid maintenance program. The self contained cable system requires the periodic checking of reservoirs and signal equipment. Oil volume and pressure records should be kept. Also, manholes should be checked on a regular basis for possible oil leaks.

The pipe type system requires that the pumping plant and signal equipment be checked periodically. Oil volume and pressure records should also be kept. Again manholes should be checked for leaks on a regular basis. Finally, the cathodic protection should be checked regularly.

It is estimated that to maintain the above programs would require an annual expenditure in excess of $2,000. This figure does not include any money for repairs which may be necessary.

No maintenance nor alarms are required for a cross-linked polyethylene insulated system since there is no leakage possible from terminations or splices. Plumbing problems normally associated with pipe type or self contained cable systems are eliminated with the solid dielectric.

The relative simplicity of the splice construction for the crosslinked polyethylene insulated cable is one of its biggest advantages. The splice requires less skilled installation personnel.

With the oil and paper insulated cable system, the plumbing problems and cable handling techniques make it absolutely necessary that an engineer or an installation supervisor from the cable manufacturer be assigned to the project for the duration of the installation. Because of the simplicity of the installation and splicing of crosslinked polyethylene cable, the overall installation time required is 50-75% less than with the pipe type cable.

As can be seen from Table 7, crosslinked polyethylene exhibits superior electrical and thermal properties to those of oil and paper insulation.

Table 7

Electrical and Thermal Properties of Crosslinked Polyethylene as Compared to Those of Oil and Paper.

	Crosslinked Polyethylene Insulation	Oil and Paper Insulation
Dielectric Constant (60 Hertz)	2.28	3.5
Power Factor (60 Hertz)	0.06%	0.29%
Loss Factor (60 Hertz)	0.14%	1.0 %
Thermal Resistivity (ohms)	350	510
Normal Operating Temp.	90°C.	80°C.

CHAPTER 6

TREEING

With the electrical and physical advantages of crosslinked polyethylene which were presented in previous chapters, plus the economic benefits which are to be presented in the next chapter, it is easy to see why it is making rapid advances as a high voltage underground cable insulation. However, the recently discovered problem of treeing is the one factor that may slow down these advances. This chapter is devoted to the history, causes and prevention of treeing in crosslinked polyethylene.

Recent microscopic analysis of polyethylene and crosslinked polyethylene insulation samples from high voltage cables, recovered after several years of service, revealed the presence, in some samples, of tree-like networks of initial breakdown channels. This deterioration phenomenon has come to be referred to as "treeing".

A great deal of research has been performed in the United States and in Japan which has increased our knowledge on the subject, but has not produced many conclusions about the cause and effect of treeing. Trees produced in solid dielectrics have been classified as either water trees, electrical trees, chemical trees or electro-chemical trees.

The electrical tree, the most serious type, is a phenomenon in which the occurrence is accompanied by electrical discharge. The treeing invariably starts at an external or internal surface of the dielectric or at an interface between the dielectric and another material. The breakdown channel ultimately destroys the stem of the tree and most of its branches. Some branches usually remain visible after failure, however, and this is taken as proof that the breakdown was preceded by tree growth.

It is believed that electrical trees occur in cable insulation only when there is a defect in its system.[10] Such trees are said to develop in a defective part of the insulation system where there are, for instance, foreign substances, protrusions in strand shield or insulation shield, or voids. In this type of insulation deterioration, two phases can be distinguished; a) Creation of the treeing (inception), which takes significant time and depends on the size of the defect, and b) tree propagation time, which is much shorter but also significant in terms of cable service life.

The chemical tree is a phenomenon in which hydrogen sulfide, or a similar compound, under conditions of no electrical stress, enters into contact with the copper conductor and causes an arborescent formation of copper sulfide. The hydrogen sulfide permeates through the jacket and insulation of the cable to finally reach the metallic conductor. The copper conductor reacts with the sulfide to produce cuprous sulfide (Cu_2S) which crystallizes and grows into the insulation to form a dendritic deposit or tree. If the dendrites of cuprous sulfide, a good electrical conductor, continue growth through the insulation, an ultimate voltage breakdown will occur.

This type of deterioration was first discovered in a thermoplastic polyethylene insulated control cable installed in a chemical plant.[11] Hydrogen sulfide from the environment went into solution with the water in which the cable was immersed. The sequence of events which was discussed in the previous paragraph occurred and the cuprous sulfide trees eventually led to insulation failure.

Subsequent laboratory investigations were performed in Japan.[11] A summary of their results concerning chemical treeing follows:

a) Chemical trees are easily reproduced in the laboratory.

b) To form the trees, there must be sufficient amounts of sulfides such as hydrogen sulfide and ammonium sulfide in the cable environment. These sulfides then proceed to permeate into the cable either in their own form or in its aqueous solutions.

c) Electrical stress is not necessary, but a continuous electrical stress appears to facilitate the development of the tree-like growths.

d) The cuprous sulfide oxidized with time to change to Cu_2O. Therefore Cu_2S and Cu_2O co-exist in the growth patterns. As the degree of oxidation increases, the Cu_2O becomes richer.

e) Cu_2S and Cu_2O, having good conductivity, result in a short circuit whenever the chemical tree completely penetrates the insulation.

The electro-chemical trees grow where electric stress is present, but they grow without electrical (corona) discharge. The trees develop slowly in wet environments and proceed over long periods of time. Their formation is linked with some kind of penetration of foreign material into the insulation under voltage stress. Thus, the electro-chemical trees differ from the chemical tree because the formation of electro-chemical trees require the presence of a voltage stress.

It differs from electrical trees because the development of electro-chemical trees require the presence of liquid (usually water). Two phases can be distinguished in the electro-chemical treeing effect: 1) Penetration of the liquid through the insulation into the conductor area. This phase seems to be accelerated by temperature. 2) The growth of the tree originating in the conductor region. This phase does not seem to be significantly influenced by the temperature.

Polyethylene cables with no conductor shield and with tape type conductor shield are extremely vulnerable to the formation of electro-chemical trees in the conductor region. Crosslinked polyethylene cables with extruded conductor shield exhibit much better resistance to treeing.

It is believed by some that dielectric breakdown occurs during a transitory stage when an electro-chemical tree converts to an electrical tree, and in that short period of time partial discharges are exhibited.[12]

Closely related to, and often confused with, electro-chemical trees are water trees. These trees also grow without electrical discharge in conditions where the dielectric and water are in contact, and in which electric stress is present. Unlike other types of trees, water trees are filled with, and only with, water. The trees gradually disappear with time when the insulation is heated in a dry environment and reappear when heated in water.

Here again, extruded conductor and insulation shields are considerably effective in retarding the rate of deterioration. A water tree is likely to grow in cases where there are abnormal protrusions in the conductor shield, as is often the case when tape type shields are used. Water seeps into such abnormal areas.

One of the important advantages of polyethylene is its excellent resistance to water penetration. This is because polyethylene is a non-polar pure hydrocarbon resin with crystallizing properties. However, the water resistance of polyethylene for actual cable insulation use is impaired by mixture with hydropholic group such as necessary antioxidants and the existence of structural defects.[10] Water in the vapor form will penetrate into the uncrystallized portions of the polyethylene.

There are two opinions on why water trees are dangerous to underground cable. The first is that the extreme deterioration of crosslinked polyethylene cable occurs with the complete penetration of the insulation by water trees.[10] The second opinion is that at higher voltages electrical trees are likely to develop at the tips of water trees.[13] The growth of other water trees is likely at the tips of the electrical trees. Thus, as the voltage stress increases, the morphology of the trees undergo complicated changes, with the water trees and electrical trees growing interdependently.

Treeing is a very diverse phenomenon which has been observed in nearly all electrical insulating materials. There are no known ways of completely eliminating treeing in crosslinked polyethylene, but steps can be taken to reduce its formation.

To prevent the reaction of sulfides with the copper conductor, two methods are available. 1) Substitute aluminum for copper as the conductor. 2) If this is not possible, block the permeation of sulfides into the cables. To do this, a newly developed sulfide capture sheath has been developed.[11] This protective layer is composed of a polyolefin composition containing metal salts which form water insoluble metal sulfides by reaction with the sulfides. The cable with a sulfide capture sheath completely traps sulfides from the environment.

Trees can form from minute voids and contaminates within the insulation. Contaminants such as metallic, carbon black, and high dielectric constant particles, can readily increase local voltage stress within the insulation and at insulation shield interfaces. Such high stress may initiate electro-chemical trees in the presence of moisture. Also liquid which may collect in voids may induce growth of these trees. Therefore, the size and number of contaminants and voids in the insulation should be reduced as much as possible. Recent developments and improvements in the cable manufacturing process have produced insulation which is far less sensitive to treeing. One important improvement is the previously mentioned triple-tandem-extrusion technique of cable manufacturing. This is proof that the basic parameters governing the formation of trees can be controlled.

The choice of crosslinked polyethylene brands and compounding ingredients is not an easy one for the utility engineer to make. Some "experts" recommend the use of crosslinked polyethylene which exhibit the best water proofness. Others contend that an insulation's resistance to moisture induced deterioration does <u>not</u> depend significantly on the insulation's permeability to water; but does depend on its resistance to the mechanism of deterioration which occurs after the moisture enters.

The addition of small amounts of specific compounds called voltage stabilizers are believed to increase treeing resistance. The voltage stabilizers function so as to alleviate an increase of local stresses generated around microscopic defects, increasing the anti-treeing characteristics of the insulation.[14] Research in this area is continuing.

There are many factors influencing the development of trees in crosslinked polyethylene. They are the cable manufacturing process, contaminants and voids in the insulation, environmental moisture and pollution, operating stress and temperature. It is likely that the proper combination occurs only infrequently with sufficient intensity to cause premature cable failures.

CHAPTER 7

COST COMPARISONS

When deciding on the type of underground system to install, one of the most important comparisons, the cost comparison, is also the most difficult. One reason for the difficulty is that the cost comparison is not a straight forward matter. It is much easier to compare the dielectric constant, or the loss factor, or the thermal resistance of various insulations than to compare the cost. The conclusion of the cost comparison is likely to differ as the following items are compared:

1. Cost of cable alone.
2. Cost of cable and installation.
3. Cost of cable and installation plus joints, terminals and cable accessories.
4. Cost of cable, installation, joints, terminals, cable accessories plus tooling, personnel training and the required back-up stock.

Similarly, it is even difficult to compare cable system costs which appear in various literature. Sometimes, total project costs are given, or frequently, cable system costs in dollars per MVA per mile are given. With insufficient information about the cable installation, these costs cannot be compared.

Another factor adding to the complexity of the situation is that almost all of the materials used in the manufacturing of underground cable are petroleum derivatives. With the current unstable economy and the unfortunate oil import situation, the prices of underground cable and accessories are subject to change at any time. Keeping these factors in mind, we can still get an idea of the cost advantages of crosslinked polyethylene when compared to the alternatives available.

As early as 1968, the economic advantages of crosslinked polyethylene cables over conventional oil and paper insulated cables were apparent for 69kV underground lines. In late 1968, a Kentucky electric utility performed a cost comparison between low pressure oil-filled paper insulated 69kV cable and crosslinked polyethylene insulated 69kV cable.[15] The comparison showed a 13.2% cost savings using the solid dielectric cable. A summary of the cost comparison is shown in Table 8 on page 47.

One of the earliest cost comparisons of crosslinked polyethylene cable systems and conventional oil-filled

Table 8

Cost Comparison

Crosslinked Polyethylene Cable System Versus Low Pressure Oil-Filled

Cable System at 69kV Voltage Level

Description	Solid Dielectric Cable 1250 MCM Aluminum	Oil-Filled Cable 800 MCM Copper
9060 ft. of 69kV low-pressure oil filled paper-insulated lead cable.		$ 44,990.
9060 ft. of 69kV solid dielectric crosslinked polyethylene cable.	$ 47,583.	
12-69kV potheads complete.		10,580.
12-69kV terminators complete.	7,645.	
6-60kV arresters, intermediate.	2,015.	2,015.
2-20 gal. oil reservoirs & associated materials.		4,950.
Other miscellaneous materials such as, korduct, steel mounting frames, conductor grounding.	2,010.	5,950.
Rights of way.	650.	650.
Company labor & crew expense.	5,905.	8,300.
Contract labor (includes concrete).	33,800.	35,500.
Technical assistance.		1,500.
Overheads - 7%	6,710.	8,070.
Total installed cost.	$106,318.	$122,505.
Percent savings in cost using solid dielectric cable.	13.2%	

cable systems at the 138kV voltage level, was performed by a Pennsylvania electric utility in early 1970.[16] These figures are presented in Table 9 on page 49. Although the current carrying capacity will vary with the type of cable and the size and type of conductor, this variation will not effect the relative position of the various systems as shown in Table 9.

A more recent cost comparison between crosslinked polyethylene cable system and low pressure oil-filled cable system at the 120kV voltage level was performed early in 1972 by a Michigan electric utility.[17] The result of this study is presented in Table 10 on page 50.

The most recent costs available are summarized in Table 11 on page 51. These costs were obtained from a cable manufacturer by the author in May 1975. A comparison is made between system components for a low pressure, self-contained, oil-filled system; a cross-linked polyethylene solid dielectric system; and a high pressure, pipe type, oil-filled system. All three systems are rated at 138kV.

A completely different, but equally important, approach to cost comparisons of underground cable systems is the cost required to transmit the power. At high voltages, 69kV and above, these costs can be quite sub-

Table 9

Cost Comparison

Crosslinked Polyethylene Cable System Versus Oil-Filled Cable Systems

at Voltage Level of 138kV.

Type of System	Conductor	Cable Cost Per 3 Phase ft.	Accessory Cost	Structural Cost	Total Project Cost
Solid dielectric, cross-linked polyethylene	1750 kcmil Aluminum	$25	$35,000	$142,000	$475,000
High pressure oil-filled pipe type	1000 kcmil Copper	18	74,000	124,000	484,000
Medium pressure oil-filled with pressurized reservoirs	2250 kcmil Aluminum	22	42,000	142,000	498,000
Medium pressure oil-filled with gravity feed	1500 kcmil Aluminum	23	78,500	142,000	534,000
Medium pressure oil-filled with pumping plant	2000 kcmil Aluminum	30	62,500	142,000	572,000

Table 10

Cost Comparison

Crosslinked Polyethylene Cable System Versus Low Pressure Oil-Filled

Cable System at 120kV Voltage Level.

System Component	Cost (Dollars)	
	Crosslinked Polyethylene	Low Pressure Oil-Filled
Cable	$ 67,000	$ 73,000
Joints	12,000	20,000
Terminals	32,000	37,000
Other Cable Accessories	0	15,000
Subtotal	$111,000	$145,000
Training and Tooling	1,000	20,000
Required Back-Up Stock	13,000	20,000
Duct System	0	62,000
Direct Burial	51,000	0
Total	$176,000	$247,000

Table 11

Cost Comparison

Crosslinked Polyethylene Cable System Components Versus Oil-Filled

Cable System Components at 138kV Voltage Level

System Component	Cost (Dollars)		
	Low Pressure Self Contained Oil-Filled	Crosslinked Polyethylene Solid Dielectric	High Pressure Pipe Type Oil-Filled
Cable (1500 kcmil Al. Conductor)	$220,400	$208,300	$117,500
Oil Reservoirs (for gravity feed)	30,200	---	---
Oil Supply Manifolds (with instruments & alarms)	2,400	---	---
Steel Pipe or Plastic Conduit	9,000*	9,000*	42,900
Pumping Plant	---	---	47,200
Oil	500	---	16,200
Electrical Supply and Joints	14,800	9,000	1,300
Potheads & Terminals	21,100	13,000	29,800
Total Components Cost	$298,400	$239,300	$254,900

* (optional)

stantial.

Generally speaking, oil-filled cables draw greater charging currents and have greater transmission losses than polyethylene insulated cables for the same voltage class. More specifically, a comparison of the cost to transmit power using various cable systems is presented in Table 12 on page 53.

The conclusions drawn from the information presented in Tables 8 through 11 is that crosslinked polyethylene insulated solid dielectric cable systems offer distinct and significant cost advantages over that of conventional systems. Crosslinked polyethylene cable systems exhibit lower cable plus components costs, possibly half that of oil and paper cable systems for some applications, and simpler installation also at less cost. Table 12 shows that solid dielectric cables display lower cost per delivered unit of power than conventional cables.

Thus, a major impetus for increased use of crosslinked polyethylene cable by utilities is that it costs less to manufacture, install and operate. These factors are of prime importance to the engineer who is responsible for the underground cable systems of an electric utility.

A cost calculation for a typical underground cable installation is shown in Appendix A on page 81.

Table 12

Cost Comparison

Cost to Transmit Power

System Voltage	Cable System	Power Transmitted	Cost to Transmit Dollars/MVA-Year-Mile
138kV	High Pressure Oil Filled Pipe-Type, Paper Insulated Forced-Cooled Cable	400 MVA	400
138kV	High Pressure Oil Filled Pipe-Type, Paper Insulated Naturally Cooled Cable	200 MVA	390
138kV	2000 kcmil Conductor, Water Cooled, Solid Dielectric Polyethylene Cable	400 MVA	350
138kV	1000 kcmil Conductor, Naturally Cooled, Directly Buried, Solid Dielectric Polyethylene Cable	200 MVA	275

CHAPTER 8

APPLICATIONS OF HIGH VOLTAGE CROSSLINKED POLYETHYLENE CABLE

In order to introduce the practical aspects of high voltage crosslinked polyethylene cable, two examples of applications are discussed below. One application was engineered totally, and one partially, by the author.

The first application was a double circuit, 69kV supply to an all electric shopping mall. The cable consisted of a 1500 kcmil aluminum conductor, (1.3 inch diameter), 45 mil semi-conducting crosslinked polyethylene conductor shield, 650 mil crosslinked polyethylene insulation, 50 mil crosslinked polyethylene semi-conducting insulation shield, 32 - #14 copper drain wires, and a 140 mil polyvinylchloride jacket. The cable diameter was 3.6 inches and weighed 4.9 pounds per foot. It was installed in a duct bank (one conductor per duct) and the line was 1500 feet long. The cable was energized in November 1969. The installation of this cable was not unusual, as 69kV solid dielectric cable was fairly common even in 1969.

The voltage gradients (stresses) that the insulation experiences at rated voltage can be easily calculated. Due to the generally uniform coaxial structure of the cable, the average radial stress is the arithmetic average stress between the conductor shield and the insulation shield.

That is:

$$\text{Average Radial Gradient} = \frac{\text{Voltage, phase to ground (volts)}}{\text{Radial thickness of insulation (mils)}} \quad (1)$$

$$= \frac{69000}{(\sqrt{3})\ (650)}$$

$$= 61.3 \text{ volts per mil}$$

The maximum radial stress occurs at the conductor shield diameter and can be determined mathematically by:

$$\text{Maximum Radial Gradient} = \frac{E \quad \text{(volts)}}{(r)\ \ln\frac{R}{r}\ \text{(mils)}} \quad (2)$$

where:

E = Voltage, phase to ground
r = radius of conductor shield in mils
R = radius of cable insulation in mils
$\ln$ = natural logarithm, base e.

$$\begin{array}{l}\text{Maximum} \\ \text{Radial} \\ \text{Gradient}\end{array} = \frac{69000 \quad (\text{volts})}{(\sqrt{3})\ (695)\ \ln \frac{1345}{695}\ (\text{mils})}$$

$$= 86.8 \text{ volts per mil}$$

The minimum radial stress occurs at the interface of the cable insulation and its shield. This can be determined mathematically by:

$$\begin{array}{l}\text{Minimum} \\ \text{Radial} \\ \text{Gradient}\end{array} = \frac{E \quad (\text{volts})}{R \ln \frac{R}{r}\ (\text{mils})} \qquad (3)$$

$$= \frac{69000}{(\sqrt{3})\ (1345)\ \ln \frac{1345}{695}}$$

$$= 44.9 \text{ volts per mil}$$

These design stresses are quite conservative by today's standards. This will become evident later in this chapter.

In 1972 it was decided that a major improvement of the highways in the vicinity of the underground line was necessary. As a result, 550 feet of the line had to be relocated.

As a first step, the splice in an existing manhole was disassembled and the terminators were removed at the substation. Pulling eyes were installed on each conductor where the splice was removed. The cable was then pulled out of the duct bank and installed on reels. Careful monitoring was performed to insure that the cable pulling tension did not exceed the manufacturer's recommendations. The reels of cable were stored while the duct bank was being relocated. A temporary overhead transmission line was used to feed the mall during this time.

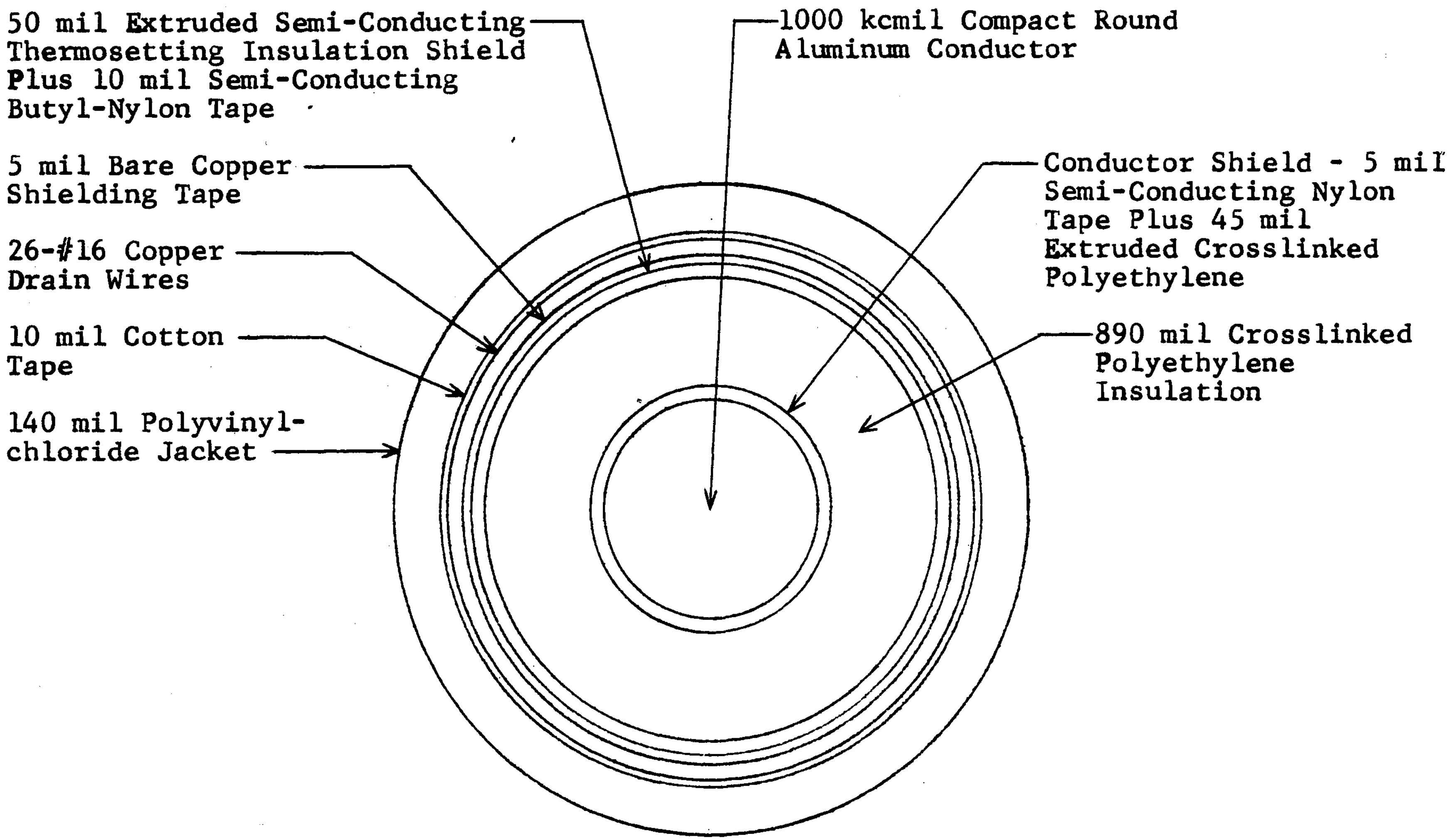
The new ducts were installed and tied into the existing ducts in the vicinity of the manhole. Eleven months after it was removed, the original cables were installed in the new duct bank. Due to the fact that the new duct run was slightly shorter than the old duct run, both ends of the cable were cut and re-prepared. A new splice was installed using a metal inert gas (MIG) welded connection and hand applied tape insulation. New terminators were installed in the substation.

All cables successfully completed the DC insulation test and are presently energized and carrying load.

Although it is possible that cables insulated with other solid dielectrics could be removed and re-used, the superior physical characteristics of crosslinked polyethylene reduced the likelihood of cable damage. It is also possible that cables insulated with oil and paper could be removed and re-used, but the problems associated with oil drainage and pressurization plus possible oil leaks would make this a very expensive and precarious venture.

The second application was the installation of a double circuit, 138kV, substation to substation tie. The installation of these circuits, by an electric utility, was a novel project due to the industry wide limited experience with 138kV solid dielectric cables. The cable consisted of a 1000 kcmil aluminum conductor (1.06 inch diameter), 5 mil semi-conducting nylon tape plus 45 mil extruded semi-conducting crosslinked polyethylene conductor shield, 890 mil crosslinked polyethylene insulation, 50 mil extruded semi-conducting thermosetting insulation shield, 10 mil semi-conducting butyl-nylon tape, 5 mil bare copper shielding tape, 26 - #16 copper drain wires, 10 mil cotton tape and 140 mil polyvinylchloride jacket (see figure 5 page 59 for pictorial description). The cable diameter was 3.65 inches and weighed 5.2 pounds per foot. It was installed in a duct bank (one conductor per duct). The line is 7000 feet long and is entirely within an urban area.

The allowable voltage gradients for this cable were more liberal then in the previous example.



<u>Figure 5</u>

Pictorial Description of 138kV Crosslinked Polyethylene Insulated Cable

Using equation (1), the average radial gradient can be determined by:

$$\begin{matrix}\text{Average}\\ \text{Radial}\\ \text{Gradient}\end{matrix} = \frac{138000 \quad \text{(volts)}}{(\sqrt{3})\ (890)\ \text{(mils)}}$$

$$= 89.5 \text{ volts per mil}$$

Using equation (2), the maximum radial gradient can be determined by:

$$\begin{matrix}\text{Maximum}\\ \text{Radial}\\ \text{Gradient}\end{matrix} = \frac{138000 \quad \text{(volts)}}{(\sqrt{3})\ (580)\ \ln \frac{1470}{580} \quad \text{(mils)}}$$

$$= 147.7 \text{ volts per mil}$$

Using equation (3), the minimum radial gradient can be determined by:

$$\begin{matrix}\text{Minimum}\\ \text{Radial}\\ \text{Gradient}\end{matrix} = \frac{138000 \quad \text{(volts)}}{(\sqrt{3})\ (1470)\ \ln \frac{1470}{580} \quad \text{(mils)}}$$

$$= 58.3 \text{ volts per mil}$$

Another unusual facet of this project is that the duct bank is located beneath the sidewalk instead of the street. The advantage of this is that during construction all lanes of traffic were left open. The only in convenience to motorists was a temporary parking restriction. Another advantage to placing the duct bank beneath the sidewalk was that there was no threat that access to a manhole would be restricted due to a parked vehicle over the manhole entrance. The only disadvantage was the close proximity of homes in some areas which made construction more time consuming. Because the sidewalk was legally considered part of the street, the cost for the right-of-way was the same whether the ducts were installed beneath the roadway or the sidewalk.

The duct bank consisted mostly of twelve conduits, encased in concrete, with a minimum ground cover of 30 inches. The ducts were arranged in three rows of four each with seven inch separation. Six conduits were occupied with 138kV cable, one conduit with a #4/0 Awg. copper ground wire and the remaining conduits were considered spares for future distribution lines. At street crossings, additional ducts were installed for possible future traffic light control cable.

Although the two circuits shared a common duct bank, separate manholes were installed. Splices for each circuit are in separate manholes for added reliability.

When this line was designed, the engineer had to insure that the cable met the following two electrical requirements: 1)that the shield capacity was sufficient and, 2) that the cable load carrying capacity was sufficient. The shield capacity was required information in the relay system design. Where required, the shield capacity can be increased by the use of concentric copper wires applied over a base copper tape to the extent necessary. Load carrying capacity calculations were performed for this installation. The results are shown in Table 13.

TABLE 13

Thermal Ampacity Ratings for 138kV Cable Installation

	Summer	Winter
Normal Conditions		
Conductor Temperature	90°C.	90°C.
Cable Capacity	560 amps.	603 amps.
Emergency Conditions		
Conductor Temperature	130°C.	130°C.
Cable Capacity	846 amps.	872 amps.

The engineer also had to design the installation within the following three physical/mechanical restraints: 1) the maximum cable pulling tension may not exceed the manufacturer's maximum allowable tension; 2) the side wall pressures exerted on the cable during the cable pulling operation may not exceed the manufacturer's maximum allowable pressure; 3) the amount of cable per cable pull may be limited by the size of the reel that the construction personnel are equipped to handle.

Calculations were made to determine the cumulative pulling tension, the sidewall pressure and cable length using the following formulas:

For a straight section:

$$T = (L)\ (W)\ (f)$$

where

T = Pulling Tension (pounds)

L = Length of duct run (feet)

W = Weight of cable (pounds/foot)

f = Coefficient of friction (Generally taken as 0.3)

For a duct section with a bend:

$$T = T_2 + T_1 \ (e^{fa})$$

where

T_2 = Tension for the straight section following the bend (pounds)

T_1 = Tension for the straight section preceding the bend (pounds)

e = natural log base (2.718)

a = angle of bend (radians)

and

$$L = (R) \ (a) \ (0.0174)$$

where

L = Length of cable in bend (feet)

R = Radius of curvature of bend (feet)

and

$$\text{Sidewall Pressure at Bend Section} = \frac{T}{R}$$

A pictoral description of the most critical pulling section is shown in Figure 6 on page 65, and the results

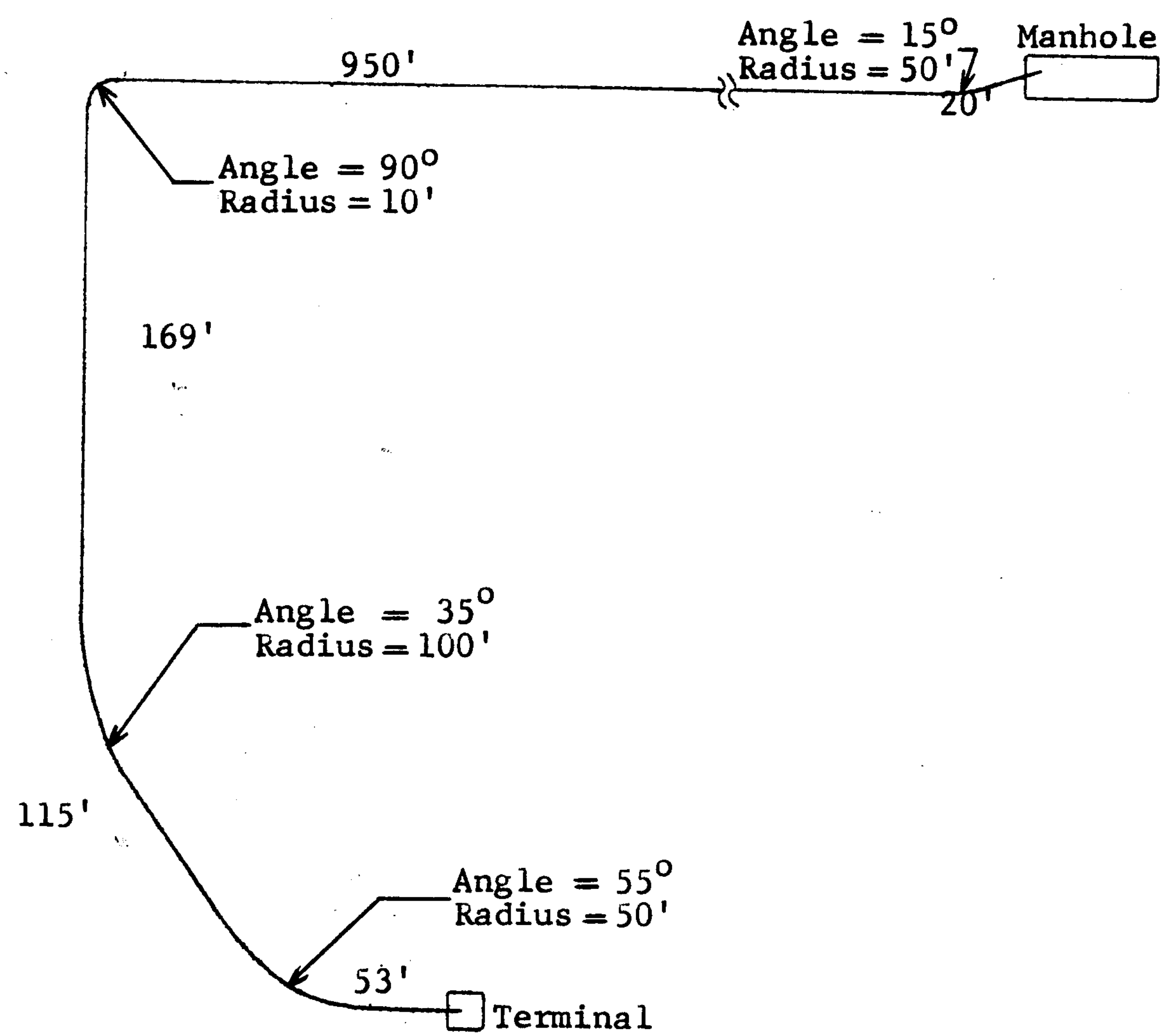


Figure 6

Pictorial Description of Critical Pulling Section of 138kV Cable System of the cumulative pulling tension and sidewall pressure are given in Table 14 on page 67.

Even with a safety factor of two, the cumulative pulling tension was below the manufacturer's maximum allowable tension of 8000 pounds and the sidewall pressure was below the manufacturer's maximum allowable pressure of 300 pounds per radius foot. The cable length permitted the use of 108 inch diameter, 76 inch wide, cable reels. These were the largest size reels that the construction personnel were equipped to use.

The line was placed in service on June 20, 1973 with a total construction cost (excluding overheads) of $825,000.

TABLE 14

Cable Pulling Tensions and Sidewall Pressures

1000 kcmil Conductor 138kV Cable

Cable Weight Per Foot 5.2 Pounds

Number of Cables Per Duct 1

Duct is 5 inches in Diameter

Coefficient of Friction is 0.30

Length of Tangent Section Feet	Bend Angle Degrees	Radius of Bend Feet	Tangent Section Pulling Tension Pounds	Cumulative Pulling Tension Pounds	Sidewall Pressure Pounds Per Radius Foot
53.0			82.7	82.7	
	55.0	50.0		110.3	2.2
115.0			179.4	289.7	
	35.0	100.0		347.9	3.5
169.0			263.6	611.6	
	90.0	10.0		979.7	98.0
950.0			1482.0	2461.7	
	15.0	50.0		2662.8	53.3
20.0			31.2	2694.0	

Manhole Location, Total Cable Length Preceding Section is 1444.9 Feet

Note: See page 66 for manufacturer's allowable values.

CHAPTER 9

CROSSLINKED POLYETHYLENE INSULATED CABLE PERFORMANCE

There are basically two ways to test the performance of an insulated cable. The first way is to obtain a section of the cable, install it, then energize it at the rated voltage, and finally note if it operates satisfactorily. To test its durability, one must attempt to keep the cable energized for thirty or forty years. Although this test is quite conclusive, it is also quite time consuming and impractical.

A second method is known as the "accelerated aging test". In this case, the cables are load-cycled under simulated service conditions. The current heating cycles, usually 12 hours on and 12 hours off, are applied at elevated voltages - often up to 150 percent of rated voltage.

The purpose of this chapter is to briefly describe the results of both types of tests as performed on high voltage, crosslinked polyethylene insulated cables.

Solid dielectric insulated cables have exhibited excellent performance records for many years at the 5kV, 12kV and 35kV voltage levels. The first significant installation of solid dielectric insulated high voltage cable was made at 69kV by a Florida electric utility in 1962.[18] After 14 months in service, a portion of this cable was removed for laboratory examination. It was reported that the cable showed no sign of deterioration.

In April 1965, a Virginia electric utility installed a short section of 69kV cable with crosslinked polyethylene insulation. It is reported that this cable is still energized and operating without failure of the cable itself.

An excerpt from the recently published 1973 cable operations report by the Edison Electric Institute is presented in Table 15 on page 70. This report, which compiles information submitted by 22 participating companies, shows a good performance record for crosslinked polyethylene insulated high voltage cables.[19]

In the field of accelerated aging tests, a considerable amount of work has been performed by cable manufacturers and by the Electric Power Research Institute at the Waltz Mill Underground Transmission Test Facility.

For example, in 1967 accelerated aging tests of 69kV crosslinked polyethylene cables were performed jointly by an electric utility and a cable manufacturer.[20] Load-

Table 15

Cable Failure Rates By Components

Insulation Material	Voltage Class: 46.1 to 69kV — Failure Rate*	46.1 to 69kV — Number of Failures	69.1 to 138kV — Failure Rate*	69.1 to 138kV — Number of Failures
Voltage Stabilized Polyethylene	9.9	3	0	0
Polyvinylchloride	3.3	1	0	0
Butyl Rubber	0	0	2.4	2
Crosslinked Polyethylene;				
Clay Filled	0	0	0	0
Carbon Black Filled	0	0	2.4	2
Unfilled	0	0	0	0

*Failure rate is number of failures reported per 1000 miles of cable cycle test results were obtained at an accelerated rate by voltage stressing continuously at 150 percent of rating and the application of two current heating cycles per 24 hour day to the desired conductor temperature.

It is significant that after being subjected to load cycles from room temperature to 130°C. for one week and from room temperature to 150°C. for one week, the power factor returned to the same value as that previous to these elevated temperature conditions.

Another way to evaluate the load-cycle test results is to observe any change in ionization factor with time and temperature. Ionization factor is the arithmetic difference in power factor measured at electrical stresses below and above operating stress. An abrupt increase in this factor is an indication of ionization within the cable.

During the accelerated aging test performed in 1967, the ionization factor remained constant. This showed the ability of the insulation to undergo thermal expansion and contraction without development of ionization.

It was partially the results of these tests that influenced the electric utility involved to install over 1200 feet of 69kV crosslinked polyethylene cable on their system shortly after the results were obtained.

Accelerated aging tests were initiated at Waltz Mill Test Facility under the direction of the Electric Power Research Institute in early 1970. Five manufacturers contributed 138kV crosslinked polyethylene insulated cable samples which were subjected to continuous and cyclic loading tests.

The tests were designed to expose the cable to cyclic operation at 150 percent rated voltage with the conductor temperature at 130°C. Two methods were employed concurrently to apply and control heat in the cables. The first was inducing load current in the cables by applying a controlled voltage to the primary of loading current transformers, which were installed around one end of the cable loop. To further elevate the cable temperature, resistance heaters were installed around the steel cable housing, which is enclosed in thermal insulation. The cable testing program was designed for a two year duration.

Due to a series of unfortunate events, every cable sample that was initially supplied failed during the tests.[21]

One cable sample failed after 40 weeks of testing. Results of the post-failure examination of the cable indicated that unusual operating problems developed as a consequence of corrosion and expansion of the unrestrained, unsealed lead sheath used in the cable. This created an insulated cable core. It is concluded that the cable failed as a result of the "insulated core" condition, and that failure was due to external discharges between semi-conductive shield and the lead sheath. It was agreed that the cable failure was due to artificial test conditions which would never be permitted in commercial practice. This is the installation of a splice which did not include a lead sleeve. Therefore, the ends of the lead sheath on each cable section were allowed to remain unsealed and unrestrained.

The cable was entirely replaced by the manufacturer with a new cable (with no lead sheath). To date, the new cable's performance has been normal and stable during the first 32 weeks of testing.

A cable sample from a second manufacturer failed approximately one year after the start of testing. This failure was ascribed to the loss of electrical contact between the lead sheath in the cable and the semi-conducting insulation shield. High resistance corrosion products had formed on the inner surface of the lead similar to the problem on the previous sample. Explanation as to the cause of the corrosion products is identical for this cable as for the previous case.

Small electro-chemical trees were detected at the extruded conductor shield-insulation interface but were judged not to be a factor in this failure. Replacement of the entire sample has been scheduled in the near future.

A cable sample from a third manufacturer actually completed the entire test program without failure. The 96 weeks of the scheduled test, which consisted of various levels of voltage and thermal acceleration, represented an estimated equivalent life of forty years. Later, it was decided to extend the test program by an additional four weeks so that the cable could be operated at a conductor temperature of 140°C. At the conclusion of this test the cable failed.

Preliminary investigations indicated that the failure was probably due to mechanical stresses rather than electrical stresses. Due to mis-operation of the temperature control thermocouples, the cable was overheated to an estimated temperature of 143°C. This had an effect on the nylon ropes which were wrapped around the cables to reduce the capacitance between the cable jacket and the enclosing metal pipes. As the cable reached the higher temperatures and expanded, the ropes became tighter around the cable. Subsequent inspection of this cable sample showed deep rope impressions in the cable jacket and distortions in the cable which matched the spiral lay of the ropes. It is likely that the ropes provided a strangulation effect that contributed to the failure.

A cable sample from a fourth manufacturer failed after one year of tests. Preliminary investigation of the cable insulation in the failed section did not reveal any conclusive evidence about the cause of the failure. This cable section was later replaced and testing continued. It was at this time that the overheating problem on the previous sample was identified. An inspection of this cable sample showed that here also the temperature control thermocouples were dislodged.

The results of a mathematical simulation showed that during the testing, the cable operated at a conductor temperature of approximately 154°C. instead of the intended 130°C. The electrical test data showed no signs of cable anomaly during these tests.

A cable sample from a fifth manufacturer failed twice during testing. The first failure also occurred after approximately one year of testing. An investigation of this faulted cable indicated that either a strand shield discontinuity or a dielectric inclusion may have initiated the failure. A splice was installed in the cable sample at the fault point and testing was resumed.

Twenty-four weeks later the second failure occurred. There is reason to believe that this cable sample was also inadvertently overheated. The cable jacket was ruptured and the metal shielding tapes were broken. Imprints of the nylon rope which was wrapped around the cable were observed on the surface of the cable.

It was unfortunate that the very expensive and time consuming testing at Waltz Mill failed to give clear cut answers about the dielectric integrity of the cable structure and on the validity of the cable designs. The testing did show some merits to the use of crosslinked polyethylene as a cable insulation. The sequence of accelerated voltages and temperatures to which these particular installations were subjected, were far more torturous than would ever be expected in normal service.

Under these conditions the cables did operate normally - although for limited periods of time.

CHAPTER 10

CONCLUSIONS

Crosslinked polyethylene has proven to be an excellent insulation for high voltage cables. There are many advantages to its use as compared to conventional cable insulations. These include superior electrical and thermal properties, lower cable costs, lower installation costs, and ease of installation, splicing and terminating. In actual operation, crosslinked polyethylene has acquired an outstanding performance record.

There have been two major setbacks in the evolution of crosslinked polyethylene as a high voltage cable insulation. The first, and most severe, was the discovery of the treeing phenomenon.

This discovery has brought with it some doubts and questions about the reliability and durability of crosslinked polyethylene insulation. Research which has been performed during the past few years, has indicated that most trees are caused by minute voids and contaminants within the insulation. With the improved cable manufacturing techniques, especially the establishment of the triple-extrusion method and the extra care taken in handling the raw materials, the occurance of trees have decreased sharply.

The other setback to the increased use of crosslinked polyethylene was the test results at Waltz Mill. Although the tests did not actually discredit the cables, they certainly did nothing to improve their creditability. It did show that high voltage solid dielectric cables require a great deal of care in manufacturing, handling and testing.

Increased use of crosslinked polyethylene insulated high voltage cable is a certainty. Crosslinked polyethylene cable has gained industry wide acceptance at voltage levels below 69kV. At the voltage levels of 69kV to 138kV, its good performance record has earned it increased confidence and subsequent increased usage. This in turn has led to the experimental development of crosslinked polyethylene insulated extra high voltage cables.

In Japan, experimental 154kV crosslinked polyethylene cables has been manufactured and are performing successfully under load cycling tests. In this country, an experimental 230kV crosslinked polyethylene insulated cable has been manufactured and is being prepared for tests.

Improvements of the insulation, such as voltage-stabilized and filled crosslinked polyethylene, are presently being examined. Variations of the cable design, such as crosslinked polyethylene cable with graded insulation, are also being tested. With this type of continued research, extra high voltage crosslinked polyethylene insulated cable will probably appear on the market within the next decade.

APPENDIX A

MATERIAL AND LABOR COSTS CALCULATIONS FOR TYPICAL HIGH VOLTAGE SOLID DIELECTRIC CABLE INSTALLATION

The following cost calculations are for a typical installation of high voltage crosslinked polyethylene insulated underground cable (see page 52). For this example the line route is 1.3 miles long and traverses a residential urban area. The double circuit line consists of six single phase conductors plus a ground wire which are installed in plastic ducts. Six manholes are required for the project. The line is installed beneath the sidewalks from one substation to another. The figures listed below include the costs for all material, and all the installation costs to dig the trench, install the conduits, install the cable splices, terminate the cable and repave the sidewalks. The costs do not include the acquisition of any required rights-of-way. (Extensions are rounded off to the nearest $100).

ITEM	UNIT COST	QUANTITY	COST
UNDERGROUND CONDUIT			
UG Conduit 5" plastic-material cost/single duct foot	$0.64/ft.	48100 ft.	$ 22,200
UG Conduit-Concrete	$28/yd.^{3}	800 yd.^{3}	22,400
UG Conduit-Installation cost/single duct foot	$0.20/ft.	48100 ft.	9,700

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ITEM	UNIT COST	QUANTITY	COST
UG Conduit-install concrete	$5/yd.^{3}	800 yd.^{3}	$ 4,000
UG Conduit-Trenching	$24/ft.	6900 ft.	166,600
Public Safety & Traffic Cont. - Labor	$2050/ mile	1.3 mile	2,700
Repave Sidewalks	$15/ft.	5300 ft.	79,500
Repave Street X-ings	$11.4/ft.	960 ft.	11,000
Repair Curb-G&W Laterals cost/ft of house frontage	$5.8/ft.	2200 ft.	12,800
MANHOLES			
Manhole-Material	$2750 each	6	16500
Manhole-Excavation	$1940 each	6	11600
Manhole-Erection	$ 650 each	6	3900
Manhole-Backfill	$ 550 each	6	3300
Duct Prep-Labor cost/single duct foot.	$0.05/ft.	48100 ft.	2400
UNDERGROUND CONDUCTOR & DEVICES			
138kV cable-material 1500 kcmil Al.	$12/ft.	45000 ft.	540,000
Cable Pulling	$1170/pull	42 pulls	49,100

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ITEM	UNIT COST	QUANTITY	COST
Cable Splices-Material	$330/splice	36 splices	11,900
Cable Splices-Labor	$1380/splice	36 splices	49,700
Sub Terminators-Material	$2250 each	12	27,000
Sub Terminators-Install Cable & Terminators	$ 800 each	12	9,600
Terminations-DC Testing	$ 525/3Ø test	8 tests	4,200
Ground Wire, Material & Labor	$0.5/ft. $100/manhole	7550 ft. 6mhs	4,400
Sub Total			$1,064,500

ENGINEERING OVERHEADS

Engineering & Supervision	1.4%	15,000
Cost Analysis & Inspection	0.5%	5,400
Interest During Construction	9.5%	101,100
Total		$1,186,000

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The author has been employed by the Pennsylvania Power and Light Company in Allentown, Pennsylvania since June, 1969. From 1969 to 1971, he held the position of Engineer in the System Planning Department. In 1971, he transferred to the Transmission Engineering Section of the Bulk Power Engineering Division and was promoted to Project Engineer in 1973. One of his duties in this capacity is the writing and updating of the Specifications for High Voltage Underground Cables.

The author has written and presented a paper entitled "PP&L's Practices and Operating Experiences Using 69kV Air Switches" for the Pennsylvania Electric Association, January, 1975 meeting. He is a member of the IEEE Power Engineering Society.

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